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EVALUATION OF MECHANICAL BEHAVIOR OF AN EPOXY STRUCTURAL ADHESIVE UNDER SHEAR LOAD

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Abstract. *This paper presents a study related to the experimental evaluation of the mechanical behavior of an epoxy structural adhesive under shear stress in an adhesively bonded steel joint. This type of adhesive has been used, in many industries, as a substitute or an auxiliary technique to some conventional union methods such as riveting, bolting and welding, especially in steel joints. However, the success of adhesion is dependent on the preparation of the metallic surface prior to application. In order to determine the effects of surface preparation on specimens, specimens with no surface treatment and with minimal treatment (cleaning and abrasion) were tested. Also, an analytical model was used to evaluate the stresses that develop in the adhesive layer. Results of analyses and experiments lead to the conclusion that the studied adhesive is adequate for adhesively bonded steel joint applications.*

Keywords: *epoxy, adhesive, shear, experimental analysis, surface treatment, analytic model*

1. INTRODUCTION

The use of epoxy-based adhesives in structural applications has increased with the profusion of synthetic adhesives in the market. This increase is due to an evolution in the bonding processes and in the applied technologies. Furthermore, these adhesives present good chemical and mechanical properties, such as: more uniform stress distribution, and higher stiffness, which lead to simpler, more economic, and more resistant steel joints (Adams and Wake, 1986; Ebnesajjad, 2008; Pasternak *et al*., 2004). For the successful application of the adhesive, the surface must receive treatment, so as to increase both the resistance and the durability of the steel joint (Adams and Wake, 1986; dos Santos, 2007).

The material chosen as the adherend was steel, because of the expressive number of applications wherein an adhesively bonded joint with epoxy can be useful. In the automotive industry, adhesive joints are used to connect panels and frames (Hoehne, 2013; Santos, 2005). In the construction industry, this type of joint is broadly adopted as a substitute to more conventional connectors (Pasternak *et al*., 2004). Moreover, steel wind turbine towers can be adhered rather than welded (Verma, 2011). The widespread adoption of adhesives demands studies of its behavior under shear. From a practical and economical standpoint, it is adequate to engage such issues concomitantly via laboratory experiments, as well as via analytical models to test and simulate use cases.

However, the scope of the present work was limited to studying the mechanical behavior of an adhesive composed of an epoxy base, under shearing stress when adhered to steel plates. In order to do that, a theoretical study of the interaction between epoxy and steel was realized, as well as the behavior of the joint in regard to the surface treatment via experimental analysis. For this purpose, an experimental test program of a double lap shear joint was designed and executed. Shear strength was also measured under conditions where the surface treatment was deliberately misapplied or not applied at all. Results were related to the adhesion mechanism and to possible modes of failure in adhesively bonded joints. An analytical model adapted from Tsai (Tsai *et al.*, 1998) was employed to evaluate the shear stresses in the adhesive layer.

2. ADHESION THEORY

The mechanisms of adhesion are yet to be fully understood and explained, and thus quite a few theories can be found in the literature. Frequently, the theoretical propositions of each theory offer their hypothesis as a comprehensive explanation of the entire phenomenon of adhesion. In the determination of the structural soundness and resistance of a joint, some theories seem to introduce geometric parameters that are difficult to measure (Kinloch, 1980). These theories assume their explanations are comprehensive, although it is likely there are still external factors left unconsidered. They usually propose explanations to the workings of the union between adhesive and substrate (adherend).Therefore, the mechanism of adhesion can be construed as a set of forces of mechanical, chemical and physical nature that act independently and are complementary. Amongst the theories, adsorption theory and mechanic of adhesion theory seem to be most widely understood and adopted (Kinloch, 1980; da Silva *et al*. 2007).

According to adsorption theory, adhesion between the substrate (adherend) and the adhesive are due to interatomic (chemical adsorption) and intermolecular (physical adsorption) forces. Thus, there is intimate contact between atoms and molecules of involved materials. Whereas mechanic of adhesion theory portrays adhesion as the mechanic anchoring between involved parts as if the adhesive would mechanically lock itself in pores, cracks, openings and other irregularities in the substrate (adherend).

3. MODES OF FAILURE

Three modes of failure can occur in the event that the adhesively bonded joints are subjected to mechanical stresses: failure in the interface of the adhesive, cohesive failure in the adhesive, and cohesive failure in the substrate (adherend). The first is associated to the interface region between the adhesive and the substrate. The second and third are related to the mechanical properties of adhesive and adherend, respectively (Ebnesajjad, 2008; Mendes, 2005). Figure 1 shows a schematic depiction of an adhesively bonded joint, and its possible modes of failure. A mixed mode of failure is also possible, i.e. two or more of the above modes of failure can occur simultaneously.

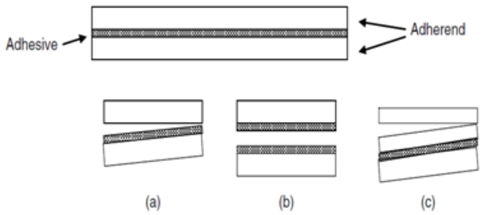

Figure 1. Schematic diagram for modes of failure in an adhesive: (a) failure in the adhesive, (b) cohesive failure in the adhesive and (c) cohesive failure in the adherend (Ebnesajjad, 2008).

The failure in the adhesive (Fig.1a) occurs in the region of interface between adhesive and adherend, and has as its main characteristic the detachment of the polymer from one of the interface surfaces with the substrate. It can be noted, post-failure, that the adhesive film remains on only one of the two interfaces with the substrate. Some hypotheses for the cause of this mode of failure are: contamination of the substrate surface, incompatibility between adherend and adhesive, absence of pressure in the curing process, absence of roughness in the surface to be adhered to (Ednesajjad, 2008).

The mode of failure of cohesive failure in the adhesive (Fig.1b) occurs with the rupture of the adhesive due to the presence of a load superior to the mechanical limit of the adhesive. Because of that, some of the adhesive material remains in both interfaces of the substrate, in the event of a failure in this mode. In the occurrence of premature cohesive failure in the adhesive, the main causes must be either the time or the temperature of the curing process.

The mode of failure of cohesive failure in the adherend (Fig.1c) occurs when both the adhesive and the interface between adhesive and adherend are more resistant than the adhering substrate (adherend). Because of that there may occur ductile yielding or brittle failure in the adherend, which is not the case if the adherend is steel.

Studies have revealed that, due to hypothetical chemical interactions and bonds between steel and polymer, most failure situations will happen primarily in the polymer, therefore presenting a cohesive nature (Adams and Wake, 1986). Therefore, the usage of adhesive in engineering projects must account for this mode of failure. Studies have also revealed that the assurance of satisfactory adhesion does not translate into an assurance of equally satisfactory cohesive resistance, since the chemical reactions that take place in the interface are not the same that take place in the interior of the adhesive polymer.

4. SURFACE TREATMENT

The concept of surface treatment or surface preparation is defined as a series of one or more operations, including but not limited to: cleaning, removal of loose particles, and physical or chemical changes to the surface to which the adhesive will be applied (Ebnesajjad, 2006). Surface preparation is meant to increase the resistance of the surface between the adjoining adhesive material and the substrate, being particularly effective at increasing the service life of the adhesive, especially when exposed to humid environments. The main reasons to perform surface treatment are (Adams and Wake, 1986; Ebnesajjad, 2006):

- Mitigation of the formation of a weaker layer in the surface of the substrate;
- Maximization of the degree of molecular interaction between the adhesive and the surface of the substrate;
- Optimization of the adhesive forces that will develop in interfaces, therefore guaranteeing a safe joint throughout its service life;
- Creation of a specific micro structured surface on the interface with the substrate.

A minimal treatment for adhesion would consist in the removal of an oxide layer, if present, and other particulates, as well as the creation of a rough surface, in order to increase the contact surface area between adhesive and substrate.

5. STRUCTURAL ADHESIVE

Structural adhesive (or structural glue) is a polymer that can be utilized to bond surfaces of two materials with the objective of producing a resistant and rigid joint. The adhesive must be capable, in these joints, to withstand the transference of stresses of considerable magnitude. Commonly, these types of adhesive are constituted by thermoset polymers that can be characterized by a network of molecules or in a reticule due to the formation of cross-linking (Vettegren' *et al.*, 2014). In the mechanics and construction industry, epoxy-based adhesives are widely adopted, because they boast excellent properties, such as: high mechanical resistance; acceptable thermal resistance; excellent rigidity and chemical resistance; high adhesion to steel and other substrates; possibility of performing the curing process at a variety of temperatures and over a variety of time spans; absence of water or volatiles during the curing process (L'Hermite, 1977). As a result of these various reasons, it is possible to obtain adhesively bonded joints with a low level of residual stresses, good cohesion, structural integrity, and excellent adhesion to many different substrates.

6. ANALYTICAL MODEL OF A DOUBLE LAP JOINT

The objective of this mathematical model is to obtain the relationship between the compression or tensile stress applied to the adherend and the shear stress to which the adhesive is subjected. This relationship is a function of the characteristics of the adhesive (shear modulus and thickness), of the substrate (elasticity modulus and thickness) and of the assemblage as a whole (width and length of the overlapping plate area).

A widely accepted model in the literature was proposed by Tsai (Tsai *et al.*, 1998). This model also takes into account stresses and deformations due to shearing in the adherend. A linear distribution is assumed for the shear stress through the thickness of the adherend. Also, a perfect connection is assumed between the adhesive and the adherend. Since it is based on Hooke's Law, it's an acceptable model for the region of the temperature domain where the polymer presents rigid behavior. The elementary model for a double lap joint test is presented in Fig. 2.

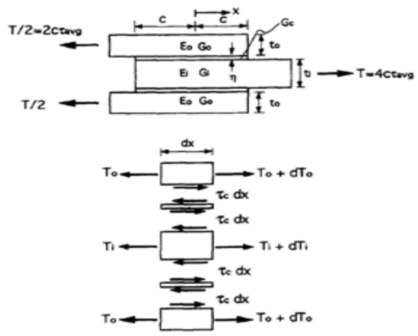

Figure 2. Geometric and material parameters of a double lap joint test (Tsai *et al*. 1998).

In Fig. 2, the overlap length is *2c* and the thickness and shear modulus of the adhesive are η and G_c, respectively. The elasticity modulus, the bulk modulus, and the thickness of the lateral substrates are E_0, G_0 and t_0, respectively. These moduli are E_i, G_i e t_i for the central substrate. Also, T_i andT_0 represent force by width, as T is an applied force by length unit.

Thus, the shear stress in the adhesive, τ_c, is as given by Equation 1:

$$\tau_c = A\, sinh(\beta x) + B\, cosh(\beta x) \tag{1}$$

where:

$$A = \frac{\beta c \tau_{avg}}{\cosh(\beta c)} \left[\frac{1 - \frac{E_i t_i}{2E_0 t_0}}{1 + \frac{E_i t_i}{2E_0 t_0}} \right] \tag{2}$$

$$B = \frac{\beta c \tau_{avg}}{\sinh(\beta c)} \tag{3}$$

$$\beta^2 = \frac{\frac{G_c}{\eta}\left(\frac{2}{E_i t_i} + \frac{1}{E_0 t_0}\right)}{1 + \frac{G_c}{\eta}\left(\frac{t_i}{6G_i} + \frac{t_0}{3G_0}\right)} \tag{4}$$

7. DOUBLE LAP JOINT TEST

7.1 Materials

Chosen materials were ASTM A36 steel and a two component epoxy-based commercial adhesive. This adhesive is composed of a white component and a black component, and it appears light gray when mixed. Table 1 presents a comparison of the properties of the adherend steel and the adhesive epoxy.

Table 1. Properties for chosen materials (Jabbar *et al.*, 2015; ABNT, 2008).

Materials	ASTM A36 steel	Adhesive
Density (kg/m^3)	7850	1650
Shear modulus (MPa)	77000	5000
Elasticity modulus (MPa)	200000	9600
Thermal dilation coefficient (^{o}C^{-1})	1.2 x 10^{-5}	2.5 x 10^{-5}
Resistance to yielding (MPa)	250	-
Resistance to failure (MPa)	400 a 550	20

7.2 Design of the test bodies

Test bodies were prepared as shown in Fig. 3a. The lateral steel plates were made to be 12.5 mm thick, 50 mm long and 70 mm high; the central plate was made to be 50 mm thick, 50 mm long and 70 mm high. The area of adhesion was of 50 cm^2 in each experiment, and the average thickness of the adhesive layer was 1 mm.

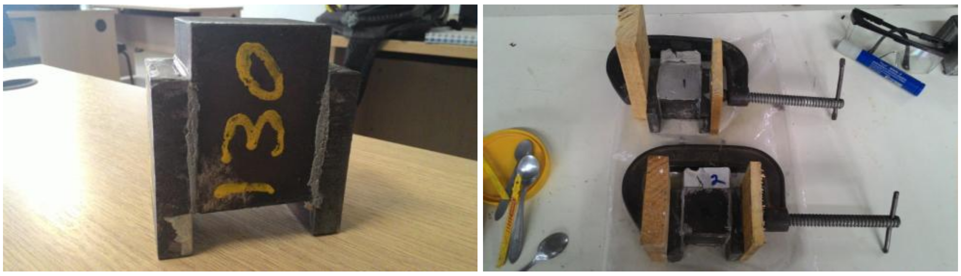

Figure 3. (a) Test body after curing process (b) Application of pressure to test bodies during curing process.

7.3 Preparation of adhesive

Adhesive components A and B were mixed in the proportion of 3:1 in mass (measured in an analytical scale) in an adequate recipient. A popsicle straw was used as a low rotation mixer, until the material presented homogeneous consistency and colors (3 minutes). In order to prevent bubbles in the mixture, the material was transferred to another recipient and mixed for about 2 more minutes, at low speeds. The curing process of this resin begins with the mixing and proceeds until 7 days later.

7.4 Application of adhesive

The adhesive was applied to the four areas for adhesion in a manner so as to further wet adhesion surfaces with the aid of a rough spatula, which was also utilized in order to control the layer to obtain proper thickness. Subsequently, a steel clamp (Fig. 3b) was employed in order to maintain constant application of pressure on the test body, this was meant to ensure there were no discontinuities or variations from the 1 mm thickness on the zone of overlap.

7.5 Minimal Treatment

The minimal treatment chosen was a cycle of cleaning, abrasion and mechanic treatment. To clean the surface, a hard brush was used to scrub the surface for adhesion. In sequence, some sandpaper was used to clear the surface of oxidation. Lastly, an emery tool was employed to further increase the roughness of the surface.

7.6 Equipment

The reaction structure is composed of a single steel frame and the reaction slab available at the Laboratory for Experimental Analysis of Structures (LAEES), in the Department of Structural Engineering. For the execution of the compression test, an MTS hydraulic actuator available at LAEES was utilized while coupled to a load cell for measurement of force intensity. Figure 4 presents the setup with focus on the machinery in (a) and presenting the test body in (b).

Figure 4.(a) Equipment used in the double lap joint test (b) Setup of the test body during the experiment.

8. ANALYSIS AND RESULTS

8.1 Experimental setup

This experiment consisted in the use of a load cell in the main slab (Fig. 4b) with the objective of measuring the resistance to shear available at the adhesive joint. The test body was adequately adjusted and centered in the hydraulic actuator and the data connections were properly connected to the data acquisition system. Loading was then performed on the test body until total separation between one of the lateral plates and the central plate. There were three main causes of structural failure: failure in the adhesive layer, detachment from the metallic surface along with the oxide layer, detachment of the adhesive layer from the metallic surface. Besides measurement of applied loads, the deformation in the adhesive layer was estimated from the measured displacements between the hydraulic actuator and the slab where test bodies were resting on with the use of two displacement transducers (DT).

The load was applied in small increments, according to a predetermined or arbitrarily imposed loading rate. The software that was used for data acquisition allowed for programmatically controlled loading application. Thus, an algorithm with two distinct phases was chosen. In the first phase of the experiment, after the application of a pre-load of 20 kN, there were 3 cycles if loading and unloading with controlled forces from 15 to 20 kN. In the second phase of the experiment, a load was applied while displacements were controlled, until failure was reached on the test bodies.

The experiments were grouped into two series. The first was denominated “A series”, and contains 6 test bodies (A1 thru A6) that were subjected to the minimal treatment mentioned in section 7.5. The second was called “B series”, and the test bodies in this series were subjected to the experiment with no treatment at all (B1 and B2), with a polished surface (B3 and B4), or there was deliberate contamination prior to the adhesion of the plates by means of a domestic cleaning product (B5 and B6). This “B series” was proposed in order to portray the indispensability of the surface treatments adopted on the test bodies of “A series” test bodies. Maximum load values on failure for each experiment are shown in Tab. 2.

Table 2. Maximum loads obtained from the experiment.

Test body	Force (kN)	Test body	Force (kN)
A1	142.6	B1	38.2
A2	110.7	B2	66.5
A3	118.0	B3	25.2
A4	105.0	B4	33.9
A5	132.6	B5	36.9
A6	98.5	B6	47.5
Average	117.8	-	-
Prescribed	90.0	-	-

Test results obtained from A series test bodies were satisfactory. Among different test bodies, maximum load values, measured in failure, were consistently higher than the resistance prescribed by the manufacturer of the epoxy-based adhesive. In these tests, the mode of failure was, also consistently, that of cohesive failure in the adhesive

(Fig. 5), which leads to the conclusion that adhesion as expected was successfully obtained. The mode of failure in thermoset polymers is brittle, because covalent bonds are broken during failure. This is confirmed by the load-displacement curve shown in Fig. 6.

Figure 5.Modes of failure: (a) Test body A1 (b) Test body A2

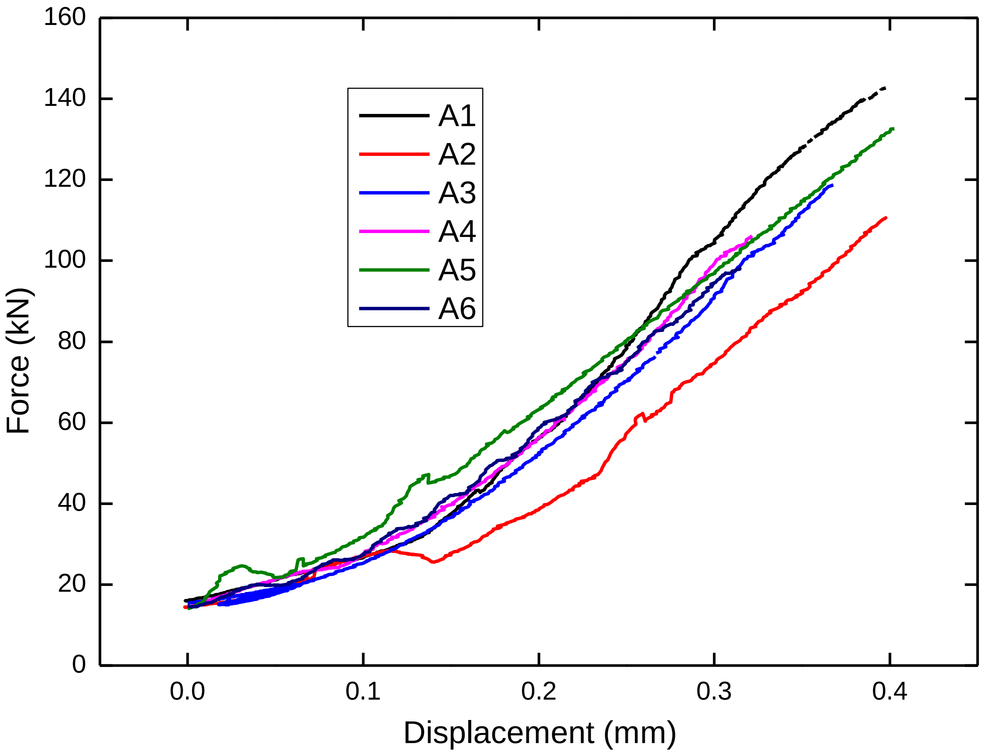

Figure 6. Load-displacement curve.

Test results obtained from test bodies of the B series have confirmed that surface treatment is indispensable in the metallic surface. Test bodies B1 and B2 were adhered without any surface treatment whatsoever (not even the oxide layer that had formed was removed from the surface of the steel). Because of this experimental choice, the failure predictably occurred in the surface oxide layer (Fig. 7a). Test body B2 reached the relatively high resistance value of a 66.5 kN force, because a small parcel of the surface failure was cohesive in the adhesive.

Test results for test bodies B3 and B4 were the smallest, since their surfaces were polished. Due to this experimental choice, there were no mechanic anchors and the interaction between adhesive and substrate was substantially reduced. This explains the reason why failure occurred as seen in Fig. 7b. A similar mode of failure also happened in the tests for test bodies B5 and B6, due to the application of a contaminant in the surfaces prior to adhesion. This product prevented interaction between adhesive and substrate.

Figure 7. Modes of failure: (a) Test body B1 (b) Test body B3 (c) Test body B5.

8.2 Analytical Model

The model used for this design was Tsai's model as described in (Tsai *et al*., 1998). Tsai's analysis introduced the concept of differential shear, illustrated in Fig 8. The reduction of the strain in both the adherends along the overlap (from A to B) and the continuity of the adhesive/adherend interface cause a non-uniform shear strain (and therefore stress) distribution in the adhesive layer.

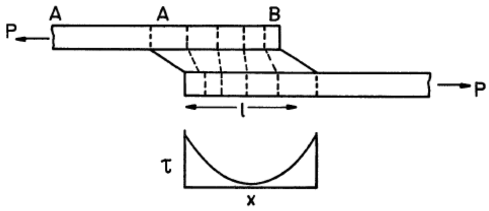

Figure 8. Deformations in loaded single-lap joints with elastic adherends (Tsai *et al*., 1998)

The shape of the shear stress distribution in Fig 9 (obtained through Eq. 1 and the properties in Tab. 1) is non-linear which can be explained by the concept of differential shear. The stresses are high at the end of overlap because of the maximum strain difference in the adherends at both ends of the adhesive layer. At the middle of the overlap both adherends have the same strain and thus lead to a lower shear stress. Figure 9 also illustrates the asymmetry in the peak stresses at the end of the joint. It can be seen that the peak shear stress at the side of the thick plate becomes lower. This is because there is less deformation, due to the higher stiffness of the plate relative to the adhesive.

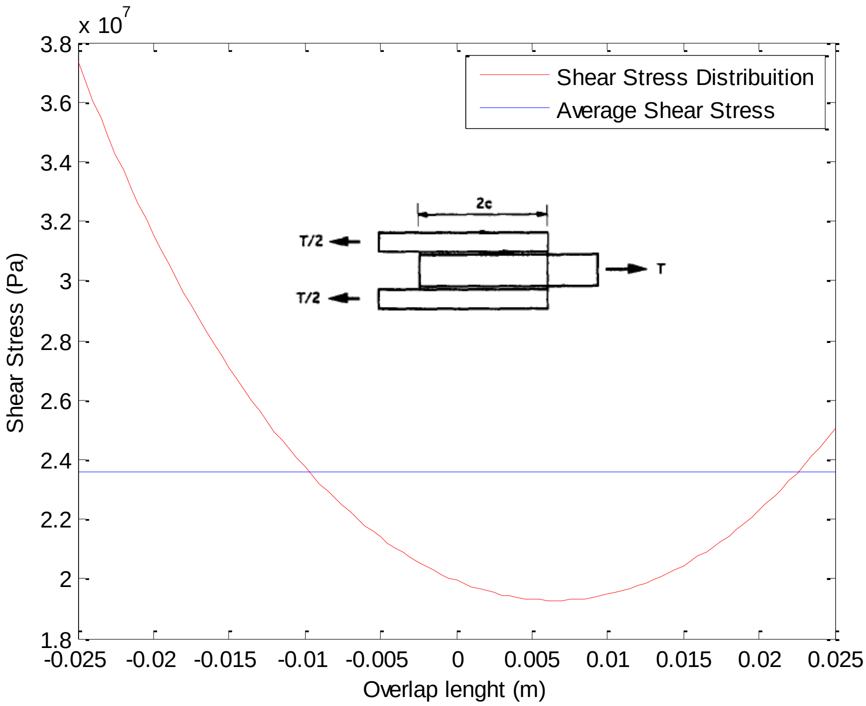

Figure 9. Shear stress assessed along the overlap length.

9. CONCLUSION

This was an analysis of the mechanical behavior of steel plates when adhesively bonded. The experimental results present both qualitative and quantitative information. It was possible to observe that the steel specimens presented different modes of failure. To determine the importance of adhesives in joint strength, it is necessary to be familiar with their mechanical properties and the chemical reactions associated with those properties. Qualitatively, experiments allow us to verify the indispensability of surface treatments in the making of adhesively bonded joints. The specific test bodies, which received minimal surface treatment, have presented cohesive failure in the adhesive, as well as failure loads well over 90 kN. The success of surface treatment is due to the elimination of the oxide layer and to the roughness obtained from the application of the emery to the adherent surface. Therefore, this structural adhesive was found to be apt for adhesion with steel. In further work, one would suggest an experimental program to evaluate the shear resistance of other types of joints that use steel/adhesive/concrete.

10. ACKNOWLEDGEMENTS

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12. RESPONSIBILITY NOTICE